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TECHNIQUE FOR ESTIMATING VENTILATION REQUIREMENTS FOR PERSONAL AIR-COOLING SYSTEMS

Final Report

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Individuals wearing encapsulating garments require auxiliary cooling systems to sustain physical and cognitive performance when exposed to high temperatures or workloads. Heat transfer in such cooling systems are typically based on either air or liquid as the heat exchange medium. Designing air-cooled systems requires knowledge of the quantity of heat to be extracted and cooling system design criteria; inlet air temperature and humidity and ventilation rates. This report addresses this issue by viewing the human as a simple time averaged heat source whose temperature must be maintained within a specified range. Integrating heat production over time permits heat extraction to be separated from physiological thermoregulation. Framing physical workload and ambient conditions in terms of military relevant scenarios for rear cabin helicopter aircrew (25 year old male working at 45% $VO_{2.\ max}$), families of curves were identified that define air-conditioning system design criteria for given conditions.

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ABSTRACT

Individuals wearing encapsulating garments require auxiliary cooling systems to sustain physical and cognitive performance when exposed to high temperatures or workloads. Heat transfer in such cooling systems are typically based on either air or liquid as the heat exchange medium. Designing air-cooled systems requires knowledge of the quantity of heat to be extracted and cooling system design criteria; inlet air temperature and humidity and ventilation rates. This report addresses this issue by viewing the human as a simple time averaged heat source whose temperature must be maintained within a specified range. Integrating heat production over time permits heat extraction to be separated from physiological thermoregulation. Framing physical workload and ambient conditions in terms of military relevant scenarios for rear cabin helicopter aircrew (25 year old male working at 45% $VO_{2,\ max}$), families of curves were identified that define air-conditioning system design criteria for given conditions.

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INTRODUCTION

Use of encapsulating protective garments in hazardous environments (chemical agents, fire fighting, hazardous waste removal) increases thermal stress on individuals by greatly diminishing the effectiveness of convective and evaporative heat exchange with the surroundings. Minimizing exposure to external heat sources, reducing workloads, extending rest periods, or providing an ancillary cooling system can ameliorate heat stress. Operational military exposures to chemical agents, however, limit beneficial actions primarily to ancillary cooling because of the nature of the tasks. Even occupational situations like fire fighting could benefit from an effective personal cooling system because task performance would increase by extending work periods.

Need for mobility argues for development of a man-mounted cooling system. Unfortunately, the inability to provide adequate cooling in a man-mounted package has plagued development of advanced field-deployable cooling systems for many years. The U.S. Army and NASA have developed efficient portable cooling systems but these depend on operating in a temperate ambient environment (references 5 and 14) or using hand-carried or backpack air-conditioners of substantial bulk and weight (reference 7). The physical constraints of both the Army system and NASA conditioning units make these approaches untenable for Navy and Marine Corps helicopter aircrews in contaminated environments.

Man-mounted personal cooling systems generally fall into two broad groups: air-cooled or liquid-cooled systems. Liquid-cooled systems have been proposed for fixed site applications, such as pilots of tactical aircraft (references 1, 6, 10, and 19), because of the cooling media heat capacity, temperature control, availability of power, and large external heat sink. Individuals needing portability, limited in available power, or suffering from other limitations, however, are constrained from using liquid cooling because of weight, power requirements, complexity, and logistic support. Air-cooled systems appear more desirable in these situations (references 5 and 14), but limited cooling capacity restricts their use.

The problem of extracting heat from mobile, physically active individuals wearing protective garments in a hot environment is particularly vexing. Helicopter or fixed-wing cargo aircraft loadmasters and firefighters exemplify this problem. The significant quantities of heat produced by high metabolic rates cannot be removed by a tethered system because of unacceptable restrictions on movement. Heavy man-mounted cooling systems, however, increase metabolic work because of the added weight that exacerbates problems of muscular fatigue and heat strain.

Optimizing the design of a cooling system, therefore, depends on balancing heat extraction rates with physical design parameters (weight, size, power). For an air-cooled system, heat exchange is a function of airstream velocity, density, and temperature. Cooling, drying, or increasing volumetric flowrates of the inlet airstream enhances heat removal. Accomplishing this, however, entails heat exchangers, air dryers, and blowers that add bulk, weight, power requirements, and complexity to be dealt with in any cooling system design.

Designing a man-mounted air-based cooling system, therefore, necessitates a compromise among these parameters. The goal of the present work is to identify operating ranges for air-cooled cooling systems based on possible inlet conditions. Past efforts at developing air-based cooling systems generally focused on identifying the best possible performance characteristics in terms of inlet air temperature and relative humidity (RH) (references 4, 5, 9, 12, 15, and 18). This approach made sense when cooling systems were severely constrained by size and power considerations. Emerging technologies, however, may provide greater range in operating parameters so a systematic approach to viable cooling strategies seems timely. The goal of this work was to establish minimal design criteria for an air-based cooling system.

METHODS

Air-cooling depends to a large extent on maintaining adequate garment ventilation. Airflow rates of >220 liters/min provide adequate cooling under certain experimental conditions (reference 16) but are difficult to achieve in a man-mounted blower system. Ventilation rates measured during recent thermal studies of the Helicopter Aircrew Integrated Life Support System (HAILSS) show airflow ranged from approximately 36-150 liter/min using the Austrian Army SAB-87 ventilation unit. Whether these lower volumetric flows are sufficient to maintain homeostasis for individuals using HAILSS or any other air-cooled system given low air temperatures and relative humidity was unknown. To answer this question, the enthalpy (heat bearing capacity) of ventilation air was calculated as a function of inlet air flowrate, temperature, and relative humidity.

Table 1 shows the inlet air-conditions chosen for analysis. Air temperatures and flow rates were selected as representative of what might be achievable with an auxiliary cooling system. Airflow rates reflect either anticipated SAB-87 output, previous study conditions (reference 16), or an arbitrary intermediate value. Total heat removal for a given set of conditions was calculated from the enthalpy difference between garment inlet and outlet airstreams. Inlet airstream enthalpy, h_{in}, was calculated for each temperature/relative humidity combination listed in table 1. Calculated outlet enthalpy, h_{out}, was based on an assumed saturated 37°C garment output airstream. These microenvironment conditions were assumed to represent a hot sweating individual wearing an encapsulating garment with skin temperatures approaching their core temperature.

Table 1
INDEPENDENT VARIABLES USED IN ANALYSIS

Airflow rate (liters/min)	50 - 300
Inlet air temperature (°C)	10 - 35
Inlet air relative humidity (%)	10 - 90

Heat extracted by garment ventilation: Having established inlet and outlet conditions, h_{in} and h_{out}, can be determined from the following set of equations (reference 2). The degree of saturation, μ, is defined for a given, the relative humidity, ϕ, by:

$$[1] \quad \mu = \phi/[1+(1-\phi)W_s/0.62198]$$

where W_s = humidity ratio of saturated air at the same temperature and pressure. The degree of saturation can also be defined at a fixed temperature and pressure as:

$$[2] \quad \mu = W/W_s$$

where W = humidity ratio of moist air. Combining equations [1] and [2]:

$$[3] \quad W = \phi W_s/[1+(1-\phi)W_s/0.62198]$$

Moist air enthalpy, h, can be calculated from W and dry bulb temperature, T, by:

$$[4] \quad h = 1.006T + W(2501 + 1.805T) \qquad \text{(kJ/kg)}$$

Combining equations [3] and [4]:

$$[5] \quad h = 1.006T + \frac{\phi W_s(2501+1.805T)}{1+(1-\phi)W_s/6.2198}$$

Equation [5] was used to calculate h_{in} for each inlet condition given in table 1 and h_{out} for T=37°C, ϕ = 1.0. Net enthalpy, Δh, for the HAILSS ventilation airstream, was subsequently calculated from:

$$[6] \quad \Delta h = h_{out} - h_{in}$$

Physiological heat production: HAILSS ventilation must remove heat generated from metabolic processes, M, and mechanical work, W, for a user to maintain thermal homeostasis (i.e., body heat storage rate, S_{body}, = 0). A balance between heat production and skin, Q_{sk}, and respiratory, Q_{res}, heat loss rates must be achieved if S_{body} = 0 which can be described mathematically as:

$$[7] \quad M + W = Q_{sk} + Q_{res} + S_{body}$$

where Q_{sk} can be partitioned into convective, C, radiant, R, and evaporative, E_{sk}, heat loss rates via the skin and Q_{res} can be partitioned into convective, C_{res}, and evaporative, E_{res}, respiratory heat loss rates.

HAILSS evaporative heat losses are likely to be substantially greater in magnitude than convective, radiant, or respiratory heat loss in a hot environment. Combined convective and radiant heat loss rates can be calculated as a function of operative temperature, T_o, and clothing thermal resistance, I_{cl}, from the following equation:

[8] $C + R = (T_{sk} - T_o)/(0.155\ I_{cl} + 1/f_{cl}h)$

where f_{cl} = ratio of clothing to skin surface area and h = combined heat transfer coefficient. Convective and radiant heat losses account for only approximately 6% of total heat loss rates under the assumed ambient conditions shown in table 2. Respiratory heat loss rates are of smaller magnitude. Consequently, the subsequent theoretical analysis considers only evaporative contributions to HAILSS heat removal based on a revised equation [7]:

[9] $M + W = E_{sk} + S_{body}$

Table 2
VARIABLES USED TO ANALYZE CONVECTIVE AND RADIANT HEAT LOSSES

Variable	Definition	Value
$\overline{\mathbf{T}}_\mathbf{r}$ mean radiant temperature	$\left[(T_g + 273.2)^4 + \frac{1.10x10^8 V_a^{.6}}{\varepsilon D^4}(T_g - T_a)\right]^{.25} - 273$	33.0
$\overline{\mathbf{T}}_\mathbf{sk}$ mean skin temperature	$.3(T_{chest} + T_{arm}) + .2(T_{thigh} + T_{shin})$	36
$\mathbf{f_{cl}}$ clothing area factor	$1.0 + .3I_{cl}$	1.39
$\mathbf{h_r}$ radiant heat transfer coefficient	$4\varepsilon\sigma\frac{A_r}{A_D}\left[273.2 + \frac{T_{cl} + \overline{T}_r}{2}\right]^3$	4.7
$\mathbf{h_c}$ convective heat transfer coefficient	3.1 when $0<V_a<.2$	3.1
H combined heat transfer coefficient	$h_r + h_c$	7.8
$\mathbf{T_o}$ Operative temperature	$\frac{h_r\overline{T}_r + h_c T_a}{h}$	33.8

T_g = globe temp., T_a = ambient air temp., V_a = air velocity, ε = emissivity, T_{chest} = upper chest temp., T_{arm} = lateral upper arm temp., T_{thigh} = anterior thigh temp., T_{shin} = lateral shin temp., I_{cl} = clothing thermal resistance (in clo units), σ = Stefan-Boltzman constant (5.67 x 10-8 W m^{-2} °K^{-4}), A_r = body effective radiation area, T_{cl} = clothing outer surface temperature

An individual's heat burden can be divided into a resting component and excess heat from mechanical work. An imposed physical workload can be divided into the energy required to perform mechanical work and energy providing additional heat to the body. Maximum physical workloads for U.S. Army helicopter pilots during various flight stages are approximately 20% $VO_{2,\,max}$ (reference 11). Physical demands on rear cabin aircrew are greater than on pilots; for purposes of this analysis, it was assumed to be 45% $VO_{2,\,max}$.

The average maximum oxygen consumption (a measure of fitness) for a 25 year old 70 kg male is approximately 3.5 liters/min (reference 13). Pedaling a bicycle ergometer at 45% $VO_{2,\,max}$ means that this average 25 year old male experiences an approximate workload of 1.58 l min-1 or 101W (6.1 kJ/min) based on the relationship:

$$[10] \quad VO_2 = 5.8w_b + 151 + 10.1\, l_w \qquad \text{(ml/min)}$$

where w_b = body weight (kg) and l_w = workload (reference 20). Since the mechanical efficiency of bicycle pedaling is roughly 30%, then this work contributes an additional 4.9 kJ/min of heat to a basal metabolic rate of 84 W (5.0 kJ/min) (reference 21). Removal of a total of 9.9 kJ/min by the ventilation system would thus be required for complete thermal homeostatsis.

If the ventilation system cannot totally remove 9.9 kJ/min, excess metabolic heat will be stored in two body compartments, core and skin, such that:

$$[11] \quad S_{body} = .9S_{core} + .1S_{skin}$$

where S_{body} = total body heat storage and S_{core}, S_{skin} = heat storage in the core and skin compartments, respectively. Solving for each body compartment, S_{core} can be calculated as a function of body mass, m_{body}, and surface area, A_D, from:

$$[12] \quad S_{core} = \frac{(1-\alpha)mC_{p,b}}{A_D}\frac{dT_{core}}{dt}$$

where α = fraction of heat stored in the skin compartment, $C_{p,b}$ = body specific heat (3.49 kJ kg^{-1} $°C^{-1}$), and T_{core} = body core temperature (reference 3). Likewise, heat storage in the skin compartment is given by:

$$[13] \quad S_{skin} = \frac{\alpha mC_{p,b}}{A_D}\frac{dT_{core}}{dt}$$

Assuming the core compartment stores 90% of retained body heat, core heat storage per hour can be determined by integrating equations [12] and [13] over 1 hr. Combining equations [11], [12], and [13] gives:

$$[14] \quad S_{core} = .034\ \Delta T_{re} = S_{body} - .004\ \Delta T_{sk} \quad (\text{kJ sec}^{-1}\ \text{m}^{-2})$$

for a 70 kg individual with body surface area = 1.8 m^2. Since:

$$[15] \quad S_{body} = M - H_{removed}$$

where M = metabolic rate (9.9 kJ min^{-1}) and $H_{removed}$ = heat removed by ventilation = Δh, then estimates of exposure times for given changes in T_{re} and T_{sk} can be obtained by combining equations [6], [14], and [15].

RESULTS

Figure 1 shows the theoretical relationship between net heat removal capacity and inlet airflow rate, temperature, and relative humidity. These results demonstrate that flow rates greater than 50 liters/min are required to maintain thermal homeostasis during light to moderate exercise regardless of inlet temperature or humidity. Even a flow rate of 300 liters/min, however, is inadequate to remove all metabolic heat at an inlet air temperature of 35°C and RH > 70%. Consequently, inlet air temperatures must be less than 35°C if one is to possibly remove all heat generated metabolically under the current assumptions.

Data from figure 1 can also be used to predict increases in T_{core} from equation [13]. Figure 2 shows how estimated times to reach 38°C core temperatures determined from predicted $\Delta \dot{T}_{core}$ depend on inlet flow rate, air temperature, and relative humidity. Flow rates of 50 liters/min or less limit exposure duration to < 2 hr before $T_{core} \geq 38°C$. Higher flow rates are predicted to permit considerably longer exposure durations (>12 hr) with inlet temperatures < 25°C and flow rates ≥ 100 liters/min.

DISCUSSION

The simplified model described in this report differs from previous modeling efforts (references 8 and 22) by attempting to establish heat extraction criteria rather than focusing on physiological changes. This model provides a straightforward means of establishing design criteria for designing air-based cooling systems. Previous experimental studies have demonstrated air-cooled systems that successfully maintain an individual's ability to tolerate hot environments for extended periods (references 14 and 15). This capability depends largely on the overall level of metabolic stress (reference 18). Even so, removing metabolically generated heat under moderate exercise loads can be accomplished with an air ventilation system given appropriate inlet air-conditions and work/rest regime (references 14 and 15). These studies focused on the maximum capabilities of the air-conditioning system but did not evaluate the overall cooling system performance parameters needed for maintaining homeostasis.

The current work attempted to identify inlet conditions which would limit rectal temperature increases to less than 1°C or 2°C over a given exposure period. Ventilation system designers can use this approach to match ventilation system properties to projected physiological responses (elevation in core temperature). Under many circumstances, especially military operations or certain industrial tasks, achieving homeostasis is not entirely necessary. Completing a specific task is the goal and elevated stress levels are acceptable within limits. If these limits are defined in terms of elevated core temperature then the present model can be used to define personal cooling system ventilation parameters.

The current analysis assumed that the overall heat burden could be determined by integrating metabolic heat production over a given exposure time. This simplifying assumption permitted this study to focus on thermodynamic considerations rather than on analyzing physiological control mechanisms. Thermoregulatory responses that increase heat losses during heat exposure (e.g., vasodilation) are accounted by integration of heat losses. In addition, relative humidity and temperature at the skin surface and in clothing layers were assumed to rise quickly during an initial period of unsteady heat losses and then achieve steady state values.

The results also strongly depend on the underlying assumption that a 50 percentile adult male represents a target population. Clearly, this does not model groups such as females or children where gender and age differences affect assumed values of metabolism, surface area, and body mass. Variability in resting metabolism, metabolic response to stress, body mass, and surface area, even within a 25 year old male population suggest that the model best serves as a nominal representation of heat losses. Redefining basic parameters (basal metabolic rate, body surface area, distribution of stored body heat, etc.) may allow this model to be used for various target populations such as females or older individuals.

Heat burdens may also be underestimated because the current model assumes an idealized relationship between work produced by bicycle ergometry and metabolic heat production. Overestimating bicycle ergometer pedaling efficiency may contribute to underestimating the necessary heat removal rate. Efficiencies of approximately 30% may be achievable when wearing typical exercise garb but is probably not reached in more bulky encumbering garments. Reducing estimated pedaling efficiency to 15% raises body heat contributed by exercise by 21% or total heat production by 9%. Metabolic responses to actual workloads experienced in the field will also differ from modeled values. Actual work involves different muscle groups, particularly upper body muscle groups, than those used in bicycle ergometry and subsequent metabolic efficiency differs markedly (reference 13). In addition, other factors such as clothing bulk, moving in cramped spaces, and less than ideal muscle loading will reduce exercise efficiency. This suggests that the present results probably represent a best case scenario and that the actual heat burden to be removed will be greater.

In summary, this report presents a simple model for determining necessary inlet air parameters for designing air-cooled personal conditioning systems. Man-mounted cooling system design requires tradeoffs between blower and cooling system weight and knowing performance parameters makes the design process easier. Modeling heat loss in this manner permits cooling system designers an easy means to estimate blower capabilities and cooling system requirements. Model improvements, such as including upper body exertion and a variable respiratory heat loss component, can be added in a step-wise fashion.

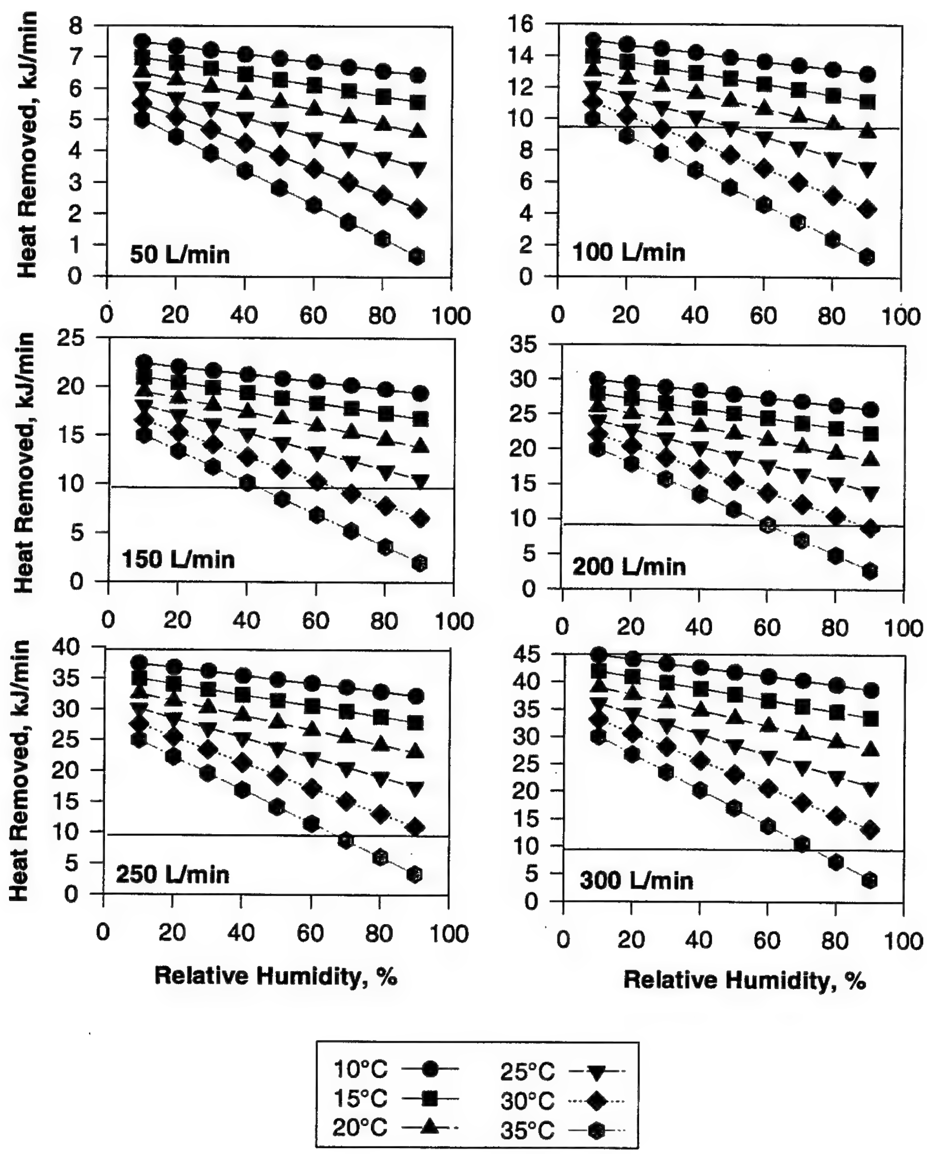

Figure 1. Heat removed as a function of flow rate, temperature, and relative humidity of inlet airstream. The solid line indicates a heat removal rate = 9.9 kJ/min.

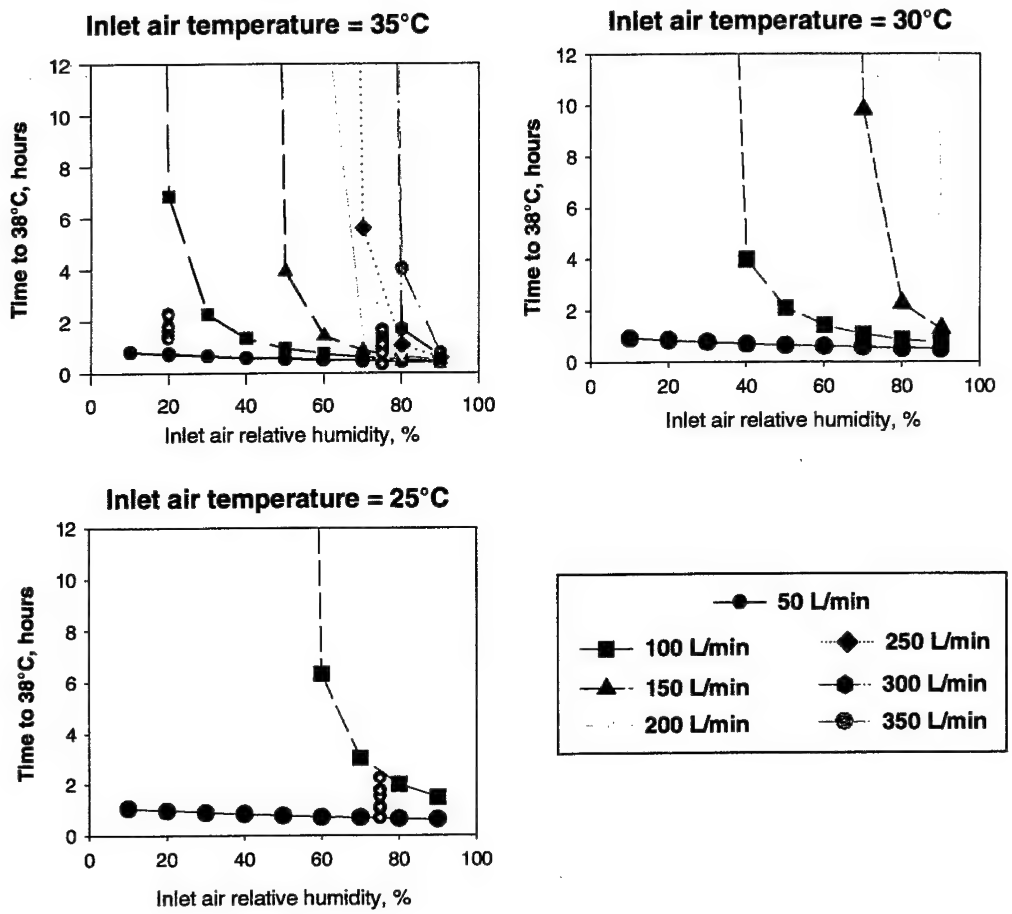

Figure 2. Predicted exposure time for the rectal temperature (T_{re}) of a moderately exercising (45% VO2max) adult male to reach 38°C. Estimated T_{re}< 38°C are anticipated for flow rates > 200 L/min (30°C) and >100 L/min (25°C). Estimated times for reaching 39°C are double those shown. Predicted exposure times for flow rates m 100 L/min at inlet temperatures of 10°C, 15°C, and 20°C are greater than 12 hours. Individual points represent experimental data from human exposures in CBR garments.

CONCLUSIONS

This study serves as a simplified approach to establishing system requirements for garment cooling systems. Analysis of these results lead to the following conclusions:

a. Blower flow rates less than 200 liters/min require inlet air temperatures of 25°C or less to completely remove metabolic heat from a moderately working male adult. The current HAILSS blower system (SAB-87) generates flow rates between 75-150 liters/min. Inlet temperatures of 20°C or less appear to be required at the lower flow rates within this range. Enthalpy in very low flow rates (< 100 liters/min) appears to be insufficient to completely remove metabolic heat at reasonable inlet temperatures (10°C-35°C) at high RH.

b. Complete removal of metabolic heat cannot be achieved with 35°C inlet air at reasonable blower flow rates (≤ 350 liters/min) unless inlet RH is fixed below 80%.

c. Fixing inlet RH at ≤ 40% allows for complete removal of metabolic heat at flow rates ≥ 150 liters/min. Complete metabolic heat removal is also possible at flow rates of 100 liters/min by lowering inlet temperatures to ≤ 25°C.

d. Incomplete metabolic heat removal may be desirable if complete heat removal proves unfeasible because tolerance times will be extended beyond those predicted for systems without any air-conditioning.

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